Citation: D.E. Groom *et al.* (Particle Data Group), Eur. Phys. Jour. **C15**, 1 (2000) (URL: http://pdg.lbl.gov)

Number of Light Neutrino Types

The neutrinos referred to in this section are those of the Standard SU(2)$\times$U(1) Electroweak Model possibly extended to allow nonzero neutrino masses. Light neutrinos are those with $m_\nu < m_Z/2$. The limits are on the number of neutrino families or species, including ν_e, ν_μ, ν_τ

THE NUMBER OF LIGHT NEUTRINO TYPES FROM COLLIDER EXPERIMENTS

Revised August 1999 by D. Karlen (Carleton University).

The most precise measurements of the number of light neutrino types, N_ν, come from studies of Z production in e^+e^- collisions. The invisible partial width, $\Gamma_{\rm inv}$, is determined by subtracting the measured visible partial widths, corresponding to Z decays into quarks and charged leptons, from the total Z width. The invisible width is assumed to be due to N_ν light neutrino species each contributing the neutrino partial width Γ_ν as given by the Standard Model. In order to reduce the model dependence, the Standard Model value for the ratio of the neutrino to charged leptonic partial widths, $(\Gamma_\nu/\Gamma_\ell)_{\rm SM} = 1.991\pm0.001$, is used instead of $(\Gamma_\nu)_{\rm SM}$ to determine the number of light neutrino types:

$$N_\nu = \frac{\Gamma_{\rm inv}}{\Gamma_\ell}\left(\frac{\Gamma_\ell}{\Gamma_\nu}\right)_{\rm SM} \quad . \tag{1}$$

The combined result from the four LEP experiments is $N_\nu = 2.984 \pm 0.008$ [1].

In the past, when only small samples of Z decays had been recorded by the LEP experiments and by the Mark II at SLC, the uncertainty in N_ν was reduced by using Standard Model fits to the measured hadronic cross sections at several center-of-mass energies near the Z resonance. Since this method is much more dependent on the Standard Model, the approach described above is favored.

Before the advent of the SLC and LEP, limits on the number of neutrino generations were placed by experiments at lower-energy e^+e^- colliders by measuring the cross section of the process $e^+e^- \rightarrow \nu\overline{\nu}\gamma$. The ASP, CELLO, MAC, MARK J, and VENUS experiments observed a total of 3.9 events above background [2], leading to a 95% CL limit of $N_\nu < 4.8$. This process has a much larger cross section at center-of-mass energies near the Z mass and has been measured at LEP by the ALEPH, DELPHI, L3, and OPAL experiments [3]. These experiments have observed several thousand such events, and the combined result is $N_\nu = 3.00 \pm 0.08$. The same process has been measured by the LEP experiments at center-of-mass energies approaching 100 GeV above the Z mass, in searches for new physics. Combined, the measured cross section is 0.965 ± 0.028 of that expected for 3 light neutrino generations [1].

Experiments at $p\overline{p}$ colliders also placed limits on N_ν by determining the total Z width from the observed ratio of $W^\pm \rightarrow \ell^\pm\nu$ to $Z \rightarrow \ell^+\ell^-$ events [4]. This involved a calculation that assumed Standard Model values for the total W width and the ratio of W and Z leptonic partial widths, and used an estimate of the ratio of Z to W production cross sections. Now that the Z width is very precisely known from the LEP experiments, the approach is now one of those used to determine the W width.

References

1. The LEP Collaborations and the LEP Electroweak Working Group, as reported by J. Mnich at the International Europhysics Conference, Tampere, Finland (July 1999).
2. VENUS: K. Abe *et al.*, Phys. Lett. **B232**, 431 (1989);

ASP: C. Hearty *et al.*, Phys. Rev. **D39**, 3207 (1989);
CELLO: H.J. Behrend *et al.*, Phys. Lett. **B215**, 186 (1988);
MAC: W.T. Ford *et al.*, Phys. Rev. **D33**, 3472 (1986);
MARK J: H. Wu, Ph.D. Thesis, Univ. Hamburg (1986).

3. L3: M. Acciarri *et al.*, Phys. Lett. **B431**, 199 (1998);
DELPHI: P. Abreu *et al.*, Z. Phys. **C74**, 577 (1997);
OPAL: R. Akers *et al.*, Z. Phys. **C65**, 47 (1995);
ALEPH: D. Buskulic *et al.*, Phys. Lett. **B313**, 520 (1993).
4. UA1: C. Albajar *et al.*, Phys. Lett. **B198**, 271 (1987);
UA2: R. Ansari *et al.*, Phys. Lett. **B186**, 440 (1987).

Number from e^+e^- Colliders

Number of Light ν Types

Our evaluation uses the invisible and leptonic widths of the Z boson from our combined fit shown in the Particle Listings for the Z Boson, and the Standard Model value Γ_ν/Γ_ℓ = 1.9908 ± 0.0015.

VALUE	DOCUMENT ID		TECN
2.994±0.012 OUR EVALUATION	Combined fit to all LEP data.		
• • • We do not use the following data for averages, fits, limits, etc. • • •			
3.00 ±0.05	[1] LEP	92	RVUE

[1] Simultaneous fits to all measured cross section data from all four LEP experiments.

Number of Light ν Types from Direct Measurement of Invisible Z Width

In the following, the invisible Z width is obtained from studies of single-photon events from the reaction $e^+e^- \to \nu\overline{\nu}\gamma$. All are obtained from LEP runs in the $E_{\rm cm}^{ee}$ range 88–94 GeV.

VALUE	DOCUMENT ID		TECN	COMMENT
3.00±0.06 OUR NEW AVERAGE	[3.07 ± 0.12 OUR 1998 AVERAGE]			
3.01±0.08	ACCIARRI	99R	L3	1998 LEP run
2.98±0.07±0.07	ACCIARRI	98G	L3	LEP 1991–1994
2.89±0.32±0.19	ABREU	97J	DLPH	1993–1994 LEP runs
3.23±0.16±0.10	AKERS	95C	OPAL	1990–1992 LEP runs
2.68±0.20±0.20	BUSKULIC	93L	ALEP	1990–1991 LEP runs
• • • We do not use the following data for averages, fits, limits, etc. • • •				
3.1 ±0.6 ±0.1	ADAM	96C	DLPH	$\sqrt{s}$ = 130, 136 GeV

Limits from Astrophysics and Cosmology

Number of Light ν Types

("light" means < about 1 MeV). See also OLIVE 81. For a review of limits based on Nucleosynthesis, Supernovae, and also on terrestial experiments, see DENEGRI 90. Also see "Big-Bang Nucleosynthesis" in this *Review*.

VALUE	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$2<N_\nu<4$	LISI	99	BBN

$<$ 4.3	OLIVE	99	BBN
$<$ 4.9	COPI	97	Cosmology
$<$ 3.6	HATA	97B	High D/H quasar abs.
$<$ 4.0	OLIVE	97	BBN; high ^{4}He and ^{7}Li
$<$ 4.7	CARDALL	96B	Cosmology, High D/H quasar abs.
$<$ 3.9	FIELDS	96	Cosmology, BBN; high ^{4}He and ^{7}Li
$<$ 4.5	KERNAN	96	Cosmology, High D/H quasar abs.
$<$ 3.6	OLIVE	95	BBN; ≥ 3 massless ν
$<$ 3.3	WALKER	91	Cosmology
$<$ 3.4	OLIVE	90	Cosmology
$<$ 4	YANG	84	Cosmology
$<$ 4	YANG	79	Cosmology
$<$ 7	STEIGMAN	77	Cosmology
	PEEBLES	71	Cosmology
$<$16	[2] SHVARTSMAN	69	Cosmology
	HOYLE	64	Cosmology

[2] SHVARTSMAN 69 limit inferred from his equations.

Number Coupling with Less Than Full Weak Strength

VALUE	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$<$20	[3] OLIVE	81C	COSM
$<$20	[3] STEIGMAN	79	COSM

[3] Limit varies with strength of coupling. See also WALKER 91.

REFERENCES FOR Limits on Number of Light Neutrino Types

ACCIARRI	99R	PL B470 268	M. Acciarri *et al.*	(L3 Collab.)
LISI	99	PR D59 123520	E. Lisi, S. Sarkar, F.L. Villante	
OLIVE	99	ASP 11 403	K.A. Olive, D. Thomas	
ACCIARRI	98G	PL B431 199	M. Acciarri *et al.*	(L3 Collab.)
ABREU	97J	ZPHY C74 577	P. Abreu *et al.*	(DELPHI Collab.)
COPI	97	PR D55 3389	C.J. Copi, D.N. Schramm, M.S. Turner	(CHIC)
HATA	97B	PR D55 540	N. Hata *et al.*	(OSU, PENN)
OLIVE	97	ASP 7 27	K.A. Olive, D. Thomas	(MINN, FLOR)
ADAM	96C	PL B380 471	W. Adam *et al.*	(DELPHI Collab.)
CARDALL	96B	APJ 472 435	C.Y. Cardall, G.M. Fuller	(UCSD)
FIELDS	96	New Ast 1 77	B.D. Fields *et al.*	(NDAM, CERN, MINN+)
KERNAN	96	PR D54 3681	P.S. Kernan, S. Sarkar	(CASE, OXFTP)
AKERS	95C	ZPHY C65 47	R. Akers *et al.*	(OPAL Collab.)
OLIVE	95	PL B354 357	K.A. Olive, G. Steigman	(MINN, OSU)
BUSKULIC	93L	PL B313 520	D. Buskulic *et al.*	(ALEPH Collab.)
LEP	92	PL B276 247	LEP *et al.*	(LEP Collabs.)
WALKER	91	APJ 376 51	T.P. Walker *et al.*	(HSCA, OSU, CHIC+)
DENEGRI	90	RMP 62 1	D. Denegri, B. Sadoulet, M. Spiro	(CERN, UCB+)
OLIVE	90	PL B236 454	K.A. Olive *et al.*	(MINN, CHIC, OSU+)
YANG	84	APJ 281 493	J. Yang *et al.*	(CHIC, BART)
OLIVE	81	APJ 246 557	K.A. Olive *et al.*	(CHIC, BART)
OLIVE	81C	NP B180 497	K.A. Olive, D.N. Schramm, G. Steigman	(EFI+)
STEIGMAN	79	PRL 43 239	G. Steigman, K.A. Olive, D.N. Schramm	(BART+)
YANG	79	APJ 227 697	J. Yang *et al.*	(CHIC, YALE, VIRG)
STEIGMAN	77	PL 66B 202	G. Steigman, D.N. Schramm, J.R. Gunn	(YALE, CHIC+)
PEEBLES	71	Physical Cosmology Princeton Univ. Press (1971)	P.Z. Peebles	(PRIN)
SHVARTSMAN	69	JETPL 9 184 Translated from ZETFP 9 315.	Shvartsman	(MOSU)
HOYLE	64	Nature 203 1108	Hoyle, Tayler	(CAMB)